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50X1-HUM

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PROPAGATION OF SOUND IN A LIQUID LAYER WITH CONSTANT GRADIENT OF
VELOCITY OF PROPAGATION

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1. Tests performed by L. D. Rosenberg in July 1946 showed a rather slow drop, with increasing distance, in intensity of sound impulses propagated in a deep sea.

In this connection we investigate here some problems connected with the propagation of sound in a deep sea. We consider here the increase of the velocity of sound with depth due to higher hydrostatic pressure. To the best knowledge of the author, the effect of this pressure on sound propagation has not been taken into account until recently.

As it will be shown below, the velocity gradient depends upon pressure and thus leads to the effect which is like the effect of whispering galleries. This effect is probably the only explanation for the propagation of sound for very great distances within the sea.

2. The gradient of the velocity of sound, depending on the increase of hydrostatic pressure, is nearly constant with depth and corresponds to a velocity variation of 1.8m/sec for every 100 m of depth. This uniformity of gradient is disturbed only in the superficial layer 100 to 200 m deep, where the velocity of sound is principally determined by the water's temperature and varies with meteorological conditions. But even when sea depths are much deeper than this superficial layer, we may consider the ideal case where the velocity gradient is constant from surface to bottom.

When the sound transmitter and receiver are located near the surface of the water, we shall get the picture of sound waves represented in figure 1.

All rays have the shape of arcs of circles and may be divided into two kinds: the rays of the first kind are bent upwards without touching the

- 1 -

CONFIDENTIAL

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bottom (e.g., the dashed line in figure 1); the second kind are reflected from the bottom (e.g., the ray represented by a dotted line). The limit of the second kind consists of a ray tangent to the bottom, represented in the figure as a continuous line. This ray has minimum reflection from the surface in comparison with other rays. The figure shows also a ray of the first kind, containing many reflections from the surface.

Every ray of the first kind, leaving point O under an angle of slide χ (angle formed by the ray with the horizontal) reaches maximum depth Z_m :

$$Z_m = \frac{1 - \cos \chi}{a \cdot \cos \chi} \quad (1)$$

and returns to the water surface a distance Δx :

$$\Delta x = \frac{2 \tan \chi}{a} \quad (2)$$

Here $a = 0.012 \text{ km}^{-1}$ is the ratio of velocity gradient to velocity of sound at the surface.

It is easy to realize that the rays of the first kind affect the concentration of sonic energy near the surface. Actually, all rays with outgoing angles of glide at point O lying between 0 and χ will be concentrated in a layer of the following thickness:

$$\frac{1 - \cos \chi}{a \cdot \cos \chi} \approx \frac{\chi^2}{2a}$$

With decreasing χ this thickness decreases with χ^2 , while the angle and hence the emitted energy decreases only with χ ; i.e., much more slowly. At the exact surface within vicinity^{the} of the radiation, the energy intensity becomes infinitely great.

This effect is completely analogous to Raleigh's effect of whispering galleries. The difference consists only in that in the case of Raleigh the boundary is curved and the radiation rectilinear, while in our case the medium boundary is straight and the radiation curved.

The infinite density of sound energy near the surface shows the inadequacy of the radiation theory in this region. However the outlining of wave computation, giving a precise picture of the sound field, is not a part of this essay.

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3. Let us investigate now the propagation of sonic impulses within the sea under these circumstances.

The passage time of an impulse along any ray of the first kind from one reflection from the surface to another reflection is given by the formula:

$$\Delta t = \frac{1}{c_0 a} \cdot \log \frac{1 + \sin \chi}{1 - \sin \chi} \quad (3)$$

where c_0 is the velocity of sound at the surface.

It is easy to prove that this time always will be shorter than the passage time of a ray along the horizontal. For a given position of transmitter and receiver, the impulse with the minimum passage time will be that following the boundary ray, represented by a continuous line in figure 1. The next one will be the impulse following the ray represented by the dashed line etc.

The more reflections a ray undergoes the later the impulse following it. The impulse propagated along the horizontal will be the last to come. Here the time interval between two consecutive impulses shortens continuously and tends to zero for the last impulses. The band of the sound recording apparatus will record a higher intensity of received sounds, because of the great condensation of impulses.

After arrival of the horizontal ray the intensity drops sharply, because thereafter only impulses with reflections from the bottom, running along rays of the second kind, will arrive. Note that these impulses come immediately after the impulse running along the boundary ray. But these result in low intensity, because they follow each other at great intervals and are weakened by reflection from the bottom.

Results obtained in L. D. Rosenberg's tests agree with above-established laws. For large enough distances the sonic energy concentrates near the end of the record. With decreasing distance the region of energy concentration shifts towards the origin.

Neglecting the superficial layer and assuming the velocity gradient to be constant along the whole depth do not essentially affect the boundary

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ray and rays in its vicinity if the sea depth is great enough in comparison with the superficial layer, because in the main part of the ray path the gradient is constant.

The superficial layer will more strongly affect rays near the horizontal ray, but the basic picture outlined above will not change radically.

If the velocity of sound decreases in the superficial layer with increasing depth, as it happens e.g., during the summer season in the sea, then rays emitted under small angles will be bent downwards without reaching the bottom. As a result the increased density of sonic energy will not occur near the surface, but in some layer below. The depth of this layer, along which the main part of the sonic energy is propagated, differs for various seas, but occurs in most cases around 100-500 m.

The author expresses his gratitude to L. D. Rosenberg for his discussion of the problems treated above.

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(Figure 1 follows)



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(DAN SSSK Vol 62
No 2, Oct 48, p 46?)

- 4 -

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